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The nitrogen economy of rice-livestock systems in Uruguay

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ABSTRACT

Over many decades there has been a global trend away from mixed farming and integrated crop-livestock systems to more-intensive single commodity systems. This has distorted local and global nutrient balances, resulting in environmental pollution as well as soil nutrient depletion. Future food systems should include integrated crop-livestock systems with tight nutrient budgets. For nitrogen (N), detailed understanding of processes, fluxes – including of gaseous forms – and budgets at a component level is needed to design productive systems with high N use efficiency (NUE) across the full nutrient chain. In Uruguay, a unique rice-livestock system has been practiced for over 50 years, attaining a high production level for rice (mean grain yields > 8 Mg ha^{-1}) and an average level for livestock (120 kg liveweight gain ha^{-1} y^{-1}). The aim of this study was to quantify the components of the N balance and NUE of this system, so as to understand its long-term sustainability, and draw conclusions for other regions. Analysis of country-level statistics for each component over the last 16 years shows tight N balances of +3.49, +2.20 and +2.22 kg N ha^{-1} yr^{-1} for rice, livestock and the whole system, respectively. Based on average values of N retained in edible food products, NUE values were 65.7, 13.2 and 23.1% for rice, livestock and the whole system, respectively. While NUE of livestock was unchanged over the period, NUE of the rice component decreased due to increasing fertiliser use. Further gains in N efficiency are possible by better integrating the system components. Actions to increase system level NUE include raising pasture and livestock productivity and controlling the increasing use of N fertilisers in rice. Tightly integrated crop-livestock systems can play a significant role in re-shaping global agriculture towards meeting food security, environmental and socioeconomic sustainability targets.

1. Introduction

The independent Scientific Panel on Responsible Plant Nutrition has recently outlined a food system approach to plant nutrition in which multiple socioeconomic, environmental and health objectives must be achieved (Scientific Panel on Responsible Plant Nutrition, 2020). The fate of nitrogen (N) in crop and livestock production is central to this because of its global impacts on sustainable food production. Nitrogen use efficiency (NUE) – here defined as the ratio of N outputs over N inputs – tends to decline as countries intensify their agriculture through increasing fertiliser use. Over time, as fertiliser management technologies, practices and regulations improve, NUE often rises again. However, the process of overcoming N surpluses is slow and remains a challenge in many parts of the world with intensive agriculture, which has both large economic and environmental consequences (Zhang et al., 2015a, 2015b). Large regional differences in N budgets and NUE exist, aggravated by transnational nutrient transfers due to the separation of crop and livestock farming, as well as increasing global trade of crops and livestock products (Grote et al., 2008; Uwizeye et al., 2020). Many high-income countries outsource much of the environmental burden of their food production to other countries, who must nonetheless ensure that their agricultural systems are both competitive and sustainable (Sun et al., 2020). Uruguay is a prime example of a country producing mostly crops and livestock for export.

On average only 16–20% of N inputs from fertiliser and other sources reach consumed products, with up to 80% lost to the environment in

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different forms along the production to consumption chain (Sutton et al., 2013; Zhang et al., 2020). In crop production, volatilisation, denitrification and leaching are the major N loss pathways, while volatilisation from excreta and leaching are the main pathways in livestock systems (Cameron et al., 2013; Oenema, 2006). Large variations have been found among countries in the full-chain NUE as well as within food supply and consumption chains within a country, depending on food consumption, the structure of the agricultural sector and how tightly crop and livestock production are integrated. In Europe, for example, full-chain NUE ranges from about 10% in Ireland to 40% in Italy (Erisman et al., 2018).

Global market drivers over many decades have caused a separation and concentration of crop and livestock farming, resulting in spatially disconnected nutrient cycles. Livestock is generally seen as having low nutrient use efficiency, high waste and large greenhouse gas (GHG) emissions (Erisman et al., 2018; Uwizeye et al., 2020). However, more sustainable livestock production is possible through pasture-based systems, re-integration of crop and livestock farming, and improved nutrient use efficiency in all parts of the system (Eisler et al., 2014). In such a more-circular farming and food system, livestock are primarily used for what they are good at: converting by-products from the food system and forage resources into valuable food and manure (Van Zanten et al., 2019). An example of such a circular crop-livestock system is the rice-livestock system in Uruguay, which has been in operation for more than five decades (Kanter et al., 2016; Pittelkow et al., 2016). This system has had continuously increasing productivity with low to moderate N fertiliser inputs. There are good records of yields and N budgets at local and national scales, providing an opportunity to understand the changing N balances and use efficiencies in the system over time. We know of no equivalent datasets for other crop-livestock systems globally.

The objectives of this study were to analyse N balances and use efficiencies in the rice-livestock system of Uruguay as a whole and in its components, with a view to drawing generic conclusions relevant to similar crop-livestock systems in other regions. We build on the studies of Pittelkow et al. (2016), which dealt with the rice componet of the system, and Kanter et al. (2016), which dealt with the livestock component. We hypothesised that the system has been following the trajectory outlined above, with initially high NUE but low yields under very low N inputs, and declining NUE and increasing N surpluses as yields increased with increasing N inputs, reaching the current status at which improvements in NUE will require fine-tuning of the system's components at the level of the full nutrient chain. We were also concerned with system N balance as this reflects the extent to which soil reserves may be mined for nutrients over time, as well as losses from the system, which may be large even though the overall inputs and outputs are in balance. We discuss major performance indicators and entry points for future improvements. Many of our findings are relevant for integrated crop-livestock systems in other parts of the world.

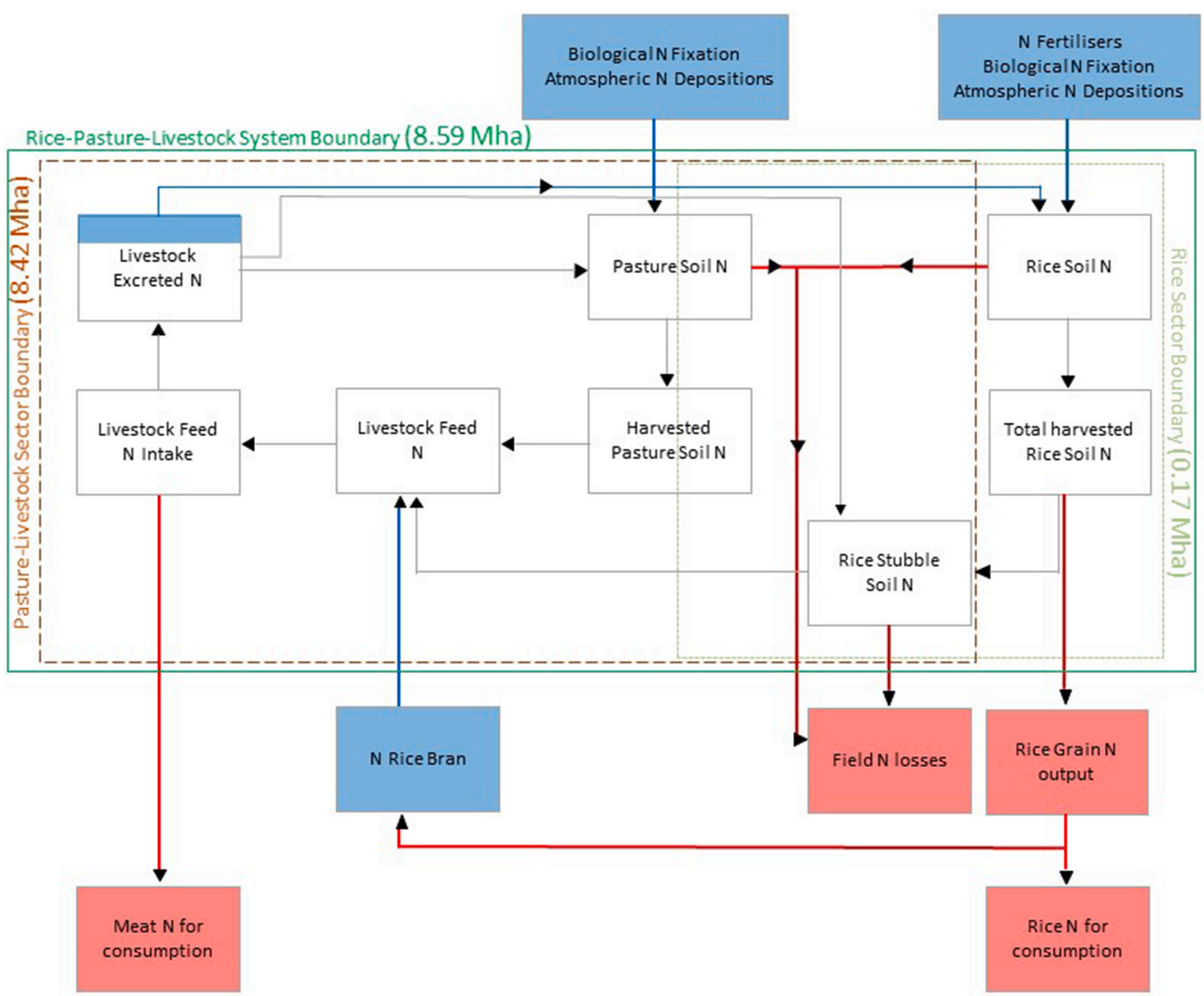

Fig. 1. Conceptual scheme of the rice-pasture-livestock system of Uruguay. Blue boxes and arrows indicate N inputs, red are the N outputs, and grey arrows show the internal N fluxes. Numbers in parenthesis indicates the area of each component (rice and pasture-livestock) or the entire system. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2. Methods

2.1. The study area

The Uruguayan rice-livestock system is carried out in 8 of the 19 counties of the country, divided into 3 producer regions. Historically, livestock and rice have been among the top five export products, contributing up to 40% to the agricultural GDP of Uruguay (Simoes and Hidalgo, 2011). The sectors are strongly integrated. Although in general different farmers manage the rice and the livestock, they are bound through agreements on the land that the rice farmer will rent each year. A conceptual scheme of the system is given in Fig. 1 with general statistical information in Table 1. In a given year, on average a total of 8.59 Mha is under livestock-pasture and rice, of which 0.68 Mha is part of the actual rice-pasture rotation, including 0.17 Mha (25%) planted with rice. Nearly 60% of the rice is planted following natural or improved pastures, and the remaining area is planted over stubble of a preceding rice crop. In both cases the land is grazed by livestock before the rice is sown. Further details are provided in Supplementary Material (SM) 1.

2.2. Scope of the study and data sources

We analysed data of rice, forage and livestock production at a national level from 2004 to 2020. We took data for the entire country separated by component, production system and food production from the Agricultural and Livestock Ministry (MGAP), the Agricultural Statistics Department (DIEA), the National Institute of Meat (INAC), the National Institute for Agricultural Research (INIA) and other literature (SM1). For the rice component, consistent data from the rice milling industry are available at a farm scale for the whole country, while data for livestock and pasture production are only available at a county scale, which means that the statistics footprint area of the latter exceeds the typical 4:1 pasture: rice area ratio in Table 1. Hence, actual total pasture area for the livestock calculations was on average 8.42 Mha, of which around 0.68 Mha was directly associated with rice (based on García et al., 2009). Despite that disparity in the scale of the data sources used, we assume that the means and general variation derived from the much larger livestock are representative for the livestock area that is directly part of the rice-pasture rotation. For example, calculated values for cattle stocking rate (0.79 livestock units ha^{-1}) and the percentage of temporary pastureland (6.3%) were similar to reported values for the main rice-livestock region of the country (0.76 livestock units ha^{-1} and 8% respectively; Simeone et al., 2008). For the computation of the rice-livestock system, land dedicated to forest production, horticulture and other crops in each county was not considered, but coverage of these uses was on average no greater than 1.5% of the total area of the counties with rice-livestock systems.

Table 1
Components of the rice-livestock system of Uruguay. Values are averages and ranges of the 2004/05 to 2019/20 growing seasons.

Parameter	Mean	Range	Units
Area of rice harvested annually	0.17	0.14–0.19	Mha
Area of natural pasture	7.56	7.35–7.88	Mha
Area of improved pasture	0.86	0.71–0.99	Mha
Area of pasture linked to rice[a]	0.68	0.56–0.76	Mha
Annual seeded past. renewable rate	16.3	14.2–18.7	%
Rice : rotation ratio	1:4.0	1:2.5–1:4.5	–
Improved pastures duration	3.8	3.0–4.5	years
Beef livestock numbers	6.26	5.96–6.66	heads × 10^6
Sheep livestock numbers	5.54	4.24–7.21	heads × 10^6
Stock density (bovine + ovine)	0.86	0.81–0.89	heads ha^{-1}

[a] Estimated area of natural plus improved pastures directly linked to the rice area based on García et al. (2009).

2.2.1. Rice

Data from rice farmers, the rice growers' association, the rice milling industry and governmental agencies are published annually. Information on rice area and yield at county and regional scale were obtained for 2004 to 2020 (DIEA, 2005; DIEA, 2020). This information covers basically all the rice farmers in the country. Data on N inputs from mineral fertiliser were sourced from annual reports of the rice milling industry summarized for the National Institute of Agricultural Research (INIA, 2020). Detailed records of fertiliser type and doses are collected by the agronomic technical teams of each of the six main rice mills. The rice area serviced by these companies covers 85–90% of the total rice area. The rice varieties grown are largely from the rice breeding program of INIA, and crop parameters, such as grain N concentration (g N kg^{-1} grain), were taken from internal records of INIA (Deambrosi et al., 2019). Because nearly 75% of the exported or internally consumed rice is processed white rice (OEC. Observatory of Economic Complexity, 2020), virtually all the bran obtained after milling (except paddy, cargo, parboiled and seed rice batches) is returned to the livestock component as animal feed. Based on Bodie et al. (2019), we assumed 11% of bran in the whole grain and 16% of protein in the bran.

2.2.2. Pasture

The forage base includes natural grassland (89.5% of area), semi-natural pastureland (4.2%) and temporary pastureland (6.3%), based on Allen et al. (2011) classification, all without N fertilisation. While natural grassland largely contains native grass species, semi-natural and temporary pasture have a mix of improved legumes (*Trifolium* spp. *and/or Lotus* spp.) and grasses (*Festuca* spp. *or Lolium* spp.), differing in productivity and duration. When legumes are included in the forage mix, at least one session of phosphorus fertilisation is frequently made (SM1). We used annual evaluation of the natural grasslands productivity based on remote sensing data of 16 years for the main ecological regions of the country (Asuaga et al., 2019). Similarly, information for the semi-natural pastureland component was taken from Martínez (2011) over 10 years. Productivity of the temporary pastureland component was estimated based on a 7-year pasture database from a local long-term experiment which rotates rice and pastures at INIA facilities (unpublished). Henceforth, we will refer to the semi-natural and temporary pastures as improved pastures. We estimate annual herbage production by regression analyses (SM1). Nitrogen availability of the different forages was estimated based on annual dry matter production, botanical composition and N content of each plant species (Carámbula, 2003), and forage utilisation and livestock N intake calculations followed Crempien (1983) (SM1).

2.2.3. Livestock

Livestock data were obtained for the period 2004 to 2020 (DICOSE, 2004; INAC, 2020; SNIG, 2020). This includes monthly reports of cattle and sheep sent to the abattoir, with animal category, live weight and kill-out percentage at a county and regional level. This information was used to calculate the meat production and N accumulated in the animals. Data from DICOSE includes all livestock categories at each farm of each county, including self-consumption on an annual basis. For this study, apart from the livestock sold to the abattoir, we included the farm self-consumption data in the meat production and N animal retention calculations. For sheep production, we also considered an average value of wool production per animal (kg per animal) in the N balance. We used international published values of N content of meat (beef and sheep meat) and wool. Wool was included together with bovine and ovine meat production under the equivalent meat concept (FAO, 2018). The amount of N recycled by livestock was defined as a function of the animal type, pasture botanical composition and herbage dry matter mass, forage utilisation (pastures or rice straw), and animal NUE (SM1).

2.3. Data analysis

We calculated a simple N balance based on N inputs minus N outputs, and NUE from outputs relative to inputs using a common N budgeting approach (Watson and Atkinson, 1999). All N inputs and outputs were evaluated within the rice-livestock system boundary and for each component separately (details in SM1). For the rice component, N inputs were fertilisers, atmospheric deposition, biological fixation, and the direct animal deposition (faeces plus urine from the 6 months of grazing prior to land preparation for rice or to un-grazed fallow); outputs were rice grain, volatilisation, denitrification and leaching. For the livestock component, N inputs were atmospheric deposition, biological fixation and rice bran as animal feed; outputs were as for the rice and animal products. Nitrogen inputs from biological fixation in pastures and rice bran in the livestock component were calculated over 0.86 Mha and 0.17 Mha respectively and assigned to the total grazing livestock area (8.42 Mha). We did not have data on changes in the soil N pools so inferred these from the balance for each component; for the whole system they are considered as internal processes and not part of the balance. For the NUE of the livestock, we considered N in rice bran returned as livestock feed as an N input. National laws prohibit use of animal by-products as feed. At a system level, animal direct deposition was considered to be internally recycled.

We then evaluated the NUE trajectory against defined low and high thresholds with a desirable N output in food products. This allows us to link the results to potential N losses. For the rice sector, we defined the upper and lower NUE thresholds as < 90 and $>50\%$ (EU Nitrogen Expert Panel, 2015; Task Force on Reactive Nitrogen, 2011), and a minimum target N output of 80 kg grain N ha^{-1} yr^{-1} which corresponds to the current average rice grain yield (8 Mg ha^{-1} at 13% moisture content and 1.15% N by dry weight) of similar productive systems in South America (Singh et al., 2017). Finally, we defined 80 kg N ha^{-1}yr^{-1} as a maximum surplus (EU Nitrogen Expert Panel, 2015) for the rice component. The term surplus is related to the potential N losses and was calculated as N inputs minus N in food products. Corresponding livestock thresholds were defined. The high and low NUE limits were defined as < 25 and $>10\%$ based on Gerber et al. (2014). A target output of 3 kg ha^{-1} yr^{-1} as animal N in edible food from extensive grazing systems was defined based on Oenema et al. (2016). A similar value can be derived from Kanter et al. (2016) as a potential value for the Uruguayan livestock sector. Because Uruguay is characterized as a net commodity product exporter with very low food imports, no feed imports and low product industrialisation, the boundary for all the analyses was defined as the farm gate.

2.4. Partial sensitivity analysis

We do not have enough data on uncertainties of all the input and output variables to make a full sensitivity analysis, but we illustrated the range of uncertainties by computing a partial sensitivity analysis as follows: for the rice component a) maintaining constant N outputs in grain, b) increasing the values of N volatilised from 20 to 40% of the N applied, denitrified from near 1–3 kg N ha^{-1}, and leached from 2 to 5 kg N ha^{-1}during the rice season based on data from irrigated rice systems with fertiliser inputs >180 kg N ha^{-1} (Jian-she et al., 2011; Xu et al., 2012); for the livestock component, a) considering the same sources of losses and the amount of N fixed by pastures which were at least doubled up to 12, 2 and 10 kg N ha^{-1} for volatilisation, denitrification and leaching respectively, and b) 78 kg N ha^{-1} for biological fixation (11 kg N ha^{-1} considering 8.42 Mha), based on intensive livestock systems without fertiliser N addition according to the Uruguayan example (FAO, 2018; Saggar et al., 2013).

3. Results

3.1. Nitrogen balance

Here we present the N balance of the entire rice-livestock system and its components averaged over the 16 year period from 2004 to 2020. On average, total N inputs to rice were 101.1 kg ha^{-1} yr^{-1} of which 66.7, 25.9 and 8.6 kg ha^{-1} yr^{-1} were fertiliser inputs, N transferred via animal direct deposition from the livestock-pasture component to the rice component, and biological N fixation plus atmospheric deposition, respectively (Fig. 2a). For the livestock-pasture component, N inputs were from atmospheric deposition (6.2 kg ha^{-1} yr^{-1}), legume pasture biological N fixation (6.8 kg ha^{-1} yr^{-1}) and the rice bran used for livestock nutrition (0.4 kg ha^{-1} yr^{-1}) (Fig. 2b) totalling on average 13.4 kg ha^{-1} yr^{-1}. The amount of inputs from fixed N by pastures and rice bran appears to be quite low once it was assigned to the total livestock area (8.42 Mha). Nevertheless, the real values for these inputs were 46 kg ha^{-1} yr^{-1} for N fixed (over 0.86 Mha) and 19 kg ha^{-1} yr^{-1} of bran availability (over 0.17 Mha). Combining both components, annual

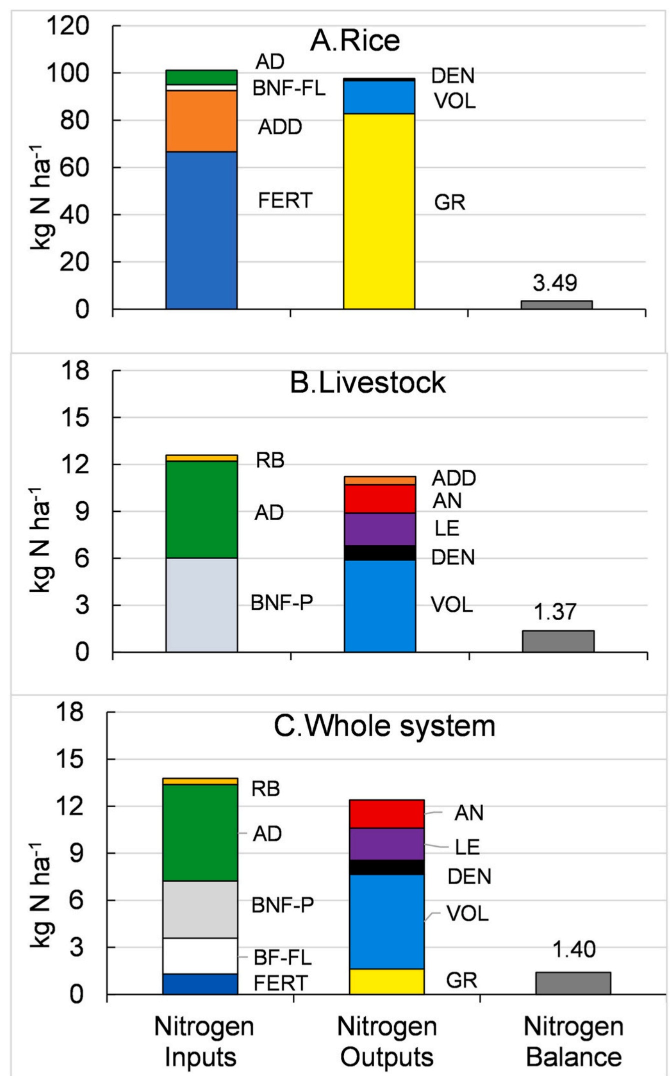

Fig. 2. Simple N balance of the rice-pasture-livestock system: (A) the rice component, (B) the pasture-livestock component, (C) the whole system. Values are averaged over 2004/5 to 2019/20. Inputs: FERT = fertilisers, ADD = animal deposition, BNF-FL = biological N fixation by free living microorganisms, AD = atmospheric deposition, BNF–P = biological fixation by pastures, RB = rice bran. Outputs: GR = N rice grain, VOL = volatilisation, DEN = denitrification, LE = leaching, AN = N whole animal.

average N input to the whole system was around 14.6 kg ha^{-1} yr^{-1} (Fig. 2c).

Total rice N output was on average 97.6 kg ha^{-1} yr^{-1}, mainly due to the large removal of N in rice grain (82.8 kg ha^{-1} yr^{-1}) and N volatilisation plus denitrification (14.9 kg ha^{-1} yr^{-1}). Outputs of the livestock-pasture component were much smaller: 11.2 kg ha^{-1} yr^{-1}, of which N associated with losses (8.9 kg ha^{-1} yr^{-1}) was greater than that in animal products (1.8 kg ha^{-1} yr^{-1}). The N transferred via animal deposition to rice was small (0.5 kg N ha^{-1} yr^{-1} on 8.42 Mha). Outputs in crop and animal products plus losses in the entire system were around 12.4 kg ha^{-1} N yr^{-1} on an annual base.

Overall, the average rice-livestock system N balance for the whole country was slightly positive during the study period (+2.22 kg ha^{-1} yr^{-1}). That value was closely related to the positive pasture-livestock component balance result of +2.20 kg ha^{-1} yr^{-1} over 8.42 M ha, but slightly increased by the positive rice component balance (+3.49 kg ha^{-1} yr^{-1}) in a smaller area (0.17 M ha).

3.2. *Full Chain-NUE and N surplus*

3.2.1. *Rice component*

On average, the full chain-NUE (N recovered in the rice grain relative to total annual N inputs) was 65.7%. When the NUE was plotted throughout the studied period, 81% of the records (except for the years 2004, 2005 and 2009) achieved optimal NUE values between the defined thresholds and exceeded the target for a desirable N output in rice edible food (80 kg N ha^{-1} yr^{-1}) (Fig. 3a). The years when the output target was not met corresponded with relatively high rainfall (INIA, 2021) prior to sowing or at the heading stage, which caused lower yields due to delayed seeding and low solar radiation. Despite the good NUE values attained, increase in N fertiliser addition (Section 3.1) shifted NUE towards the lower threshold (≤50%) in the later years (Fig. 3a). This is due to reduced N transfer into grain and N losses to the environment. Thus, there was a negative correlation ($r = -0.96$) between NUE and N surplus values so that when NUE was maximum, the N surplus was minimum and vice versa (Fig. 4a).

3.2.2. *Livestock component*

The expected NUE of the livestock component is low due to a much smaller N output in animal edible products in this extensively managed, grazing-based livestock system. On average, livestock NUE was 13.2% and annual values were between the defined upper and lower NUE

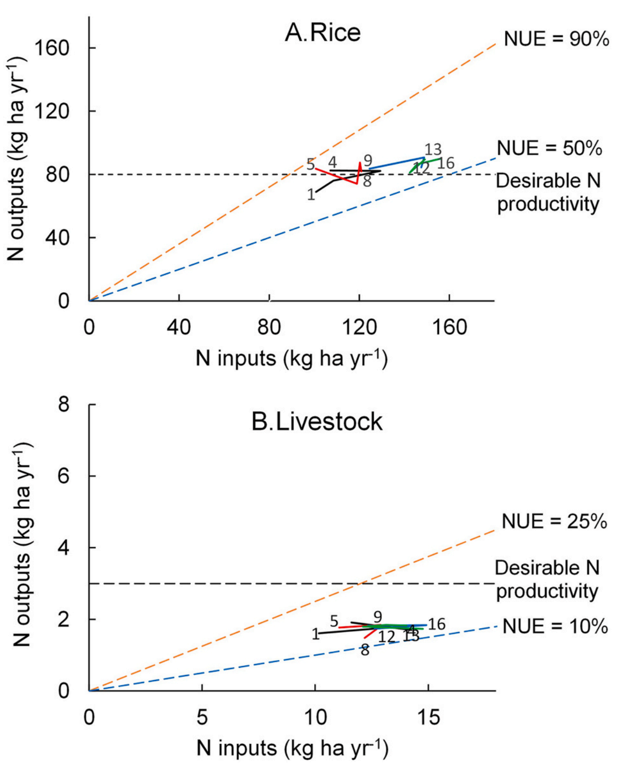

Fig. 3. Changes in N outputs versus inputs from the 2004/5 to the 2019/20 growing seasons: (A) rice component, (B) livestock component. Solid black, red, blue and green lines indicate changes from the 1st to 4th, 5th to 8th, 9th to 12th and 13th to 16th years of the series, respectively. Dashed orange and blue lines indicate NUE (= outputs/inputs × 100) of 90 and 50%, respectively for rice and 25 and 10%, respectively for livestock. Dashed black lines indicate the expected N output for a desirable level of production. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

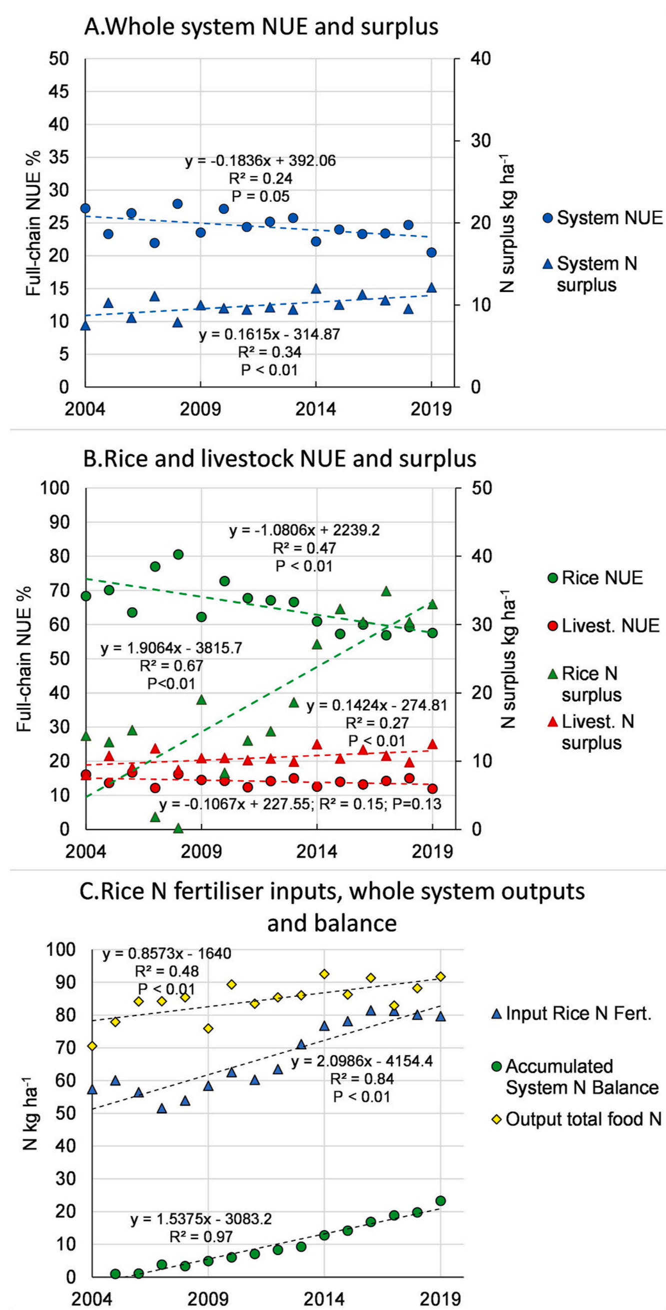

Fig. 4. Changes from 2004/5 to 2019/20 in NUE (= outputs/inputs × 100) and N surplus (= inputs − outputs) in (A.) the whole system and (B) the rice and livestock components; (C) N inputs, outputs and balance in the whole system.

boundaries, but below the desirable minimum N productivity output of 3 kg ha^{-1} yr^{-1}. Similar to the rice component, NUE tended to decrease in later years of the study, due to plateauing N outputs in meat and a slight increase of N inputs in the last 4 years (Fig. 3b) due to a greater area of improved pastures with N fixing legumes. Nonetheless, the changes in NUE and N surplus were smaller than in the rice component and were steady over the study period (Fig. 4a).

3.2.3. Rice-livestock system

Over 16 years, the mean value of N retained in both food products for the entire system was 23.1%. As shown for each component, system NUE decreased over time (−11.4%) (Fig. 4a), close to what was observed for the livestock component (−11.7%) but smaller than the fall in rice NUE (−22.0%) (Fig. 4b). The N surplus at a system level remained almost unchanged at low levels (9.9 kg ha^{-1} yr^{-1} on average) although this value was mainly influenced by the low N surplus in the livestock component (10.5 kg ha^{-1} yr^{-1}) compared with the rice component, which experienced an increase of 28.6 kg in the N surplus over the period. A positive balance in the rice component due to an upward trend in N fertiliser added (+31.5 kg N ha^{-1} from 2004 to 2020), greater than the increase in yield and N output in rice grain (+12.8 kg ha^{-1}), explained increasing N surplus as well as the change in the N accumulated balance from −1.29 kg ha^{-1} to +38.6 kg ha^{-1} (Fig. 4c).

4. Discussion

The Uruguayan rice-livestock system is highly integrated within regions and production cycles, combining one of the world's most productive rice systems (yields > 8 Mg ha^{-1}) with grazing-based average livestock productivity for meat. The low average N fertiliser inputs (67 kg ha^{-1} yr^{-1}), accounting for 66% of total rice N inputs and 81% of grain N, might mean negative soil N balances and mining of soil N over time. However, we found that substantial amounts of N are contributed by animal deposition, accounting for 26% and 31% of total rice inputs and grain removal, respectively. Similarly, in other mixed farming systems, over 20% of the N for crop production comes from livestock (Liu et al., 2010).

At the beginning of the period studied here, some years were close to the high NUE threshold (≥90%), which could raise concerns about sustaining soil health. However, the system has been in operation for 50 years with no signs of land degradation or declining yields. Country-average rice yields have increased from <5 Mg ha^{-1} in the early 1990s to about 8 Mg ha^{-1} in recent years, with some farmers reaching 10 Mg ha^{-1} or more (Tseng et al., 2020). It has also been shown that soil organic carbon is maintained under rice rotations that include improved pastures (Deambrosi, 2009). However the inclusion of improved pastures in the rotation, or a higher crop intensity vs pasture length, could alter the amounts of nutrients recycled by livestock, and could also change the current near-neutral N balance (+3.49 kg ha^{-1} yr^{-1}). Overall, and strongly influenced by the livestock sector, the entire system has maintained an adequate balance between N inputs and outputs, resulting in very low N surpluses and no noticeable deterioration of soil health.

Assuming the proposed enlarged values of losses mentioned for the partial sensitivity analysis, N balance would reach −2 kg N ha^{-1} yr^{-1} for the rice system and less than −10 kg N ha^{-1} yr^{-1} for the livestock and whole system respectively. That means that, even if our calculations under- or over-estimate the losses or N inputs or both, the magnitude of the balance suggests that soil N changes would be less than detection limits. Because the rice and livestock are produced for export, it is important that production can be shown to be environmentally benign. For this, improving records, particularly of N losses from the system, will be important.

Despite an upward trend in rice yield, the recent increase in N fertiliser application to rice (Pittelkow et al., 2016) has decreased the system NUE and shifted the N balance slightly towards surplus. Our results suggest that the Uruguayan rice-livestock system is approaching the end of the first stage of this process with still increasing fertilisation rates. This can be observed in the NUE of the most recent years in our time series, when the relation between inputs and outputs approached the lower threshold of NUE. Despite the recent decrease in NUE, the average for rice during the entire 2004–2020 period was high (65.7%) compared with pure upland crop systems (Jarvis et al., 2011), systems including N fixing crops or pastures (Godinot et al., 2016) or rice systems in Asia (Singh et al., 2017), and close to a desirable future target of 70% (Scientific Panel on Responsible Plant Nutrition, 2020). In addition, this high average NUE is associated with an N surplus of only around 20 kg ha^{-1} yr^{-1}, still far from the defined upper threshold (80 kg ha^{-1} yr^{-1}). This is contrary to findings for other systems where high yields and NUE may still result in relatively high N surpluses (Silva et al., 2021).

Because livestock N inputs and outputs were more constant over the period analysed, NUE and N surplus tended to plateau. The average NUE (13.2%) was in the range of published values internationally (Gerber et al., 2014; Jarvis et al., 2011). At a system level, NUE and surplus values were closer to those for the livestock component because of its greater extent than the rice. Although NUE comparisons among systems may be confounded by differences in methods or defined boundaries, the NUE of this rice-livestock system (23.1%) is only slightly higher than values reported for other systems (Galloway and Cowling, 2002; Howarth et al., 2002). In integrated systems, NUE values between 35% (Godinot et al., 2015) and 45% (Westhoek et al., 2014) are attained only when the proportion of the crop component greatly exceeds the livestock.

A key question is whether the system's NUE could be improved further whilst preserving the low N surplus. Should efforts be concentrated on the rice component which has already achieved high NUE and capture of N, or on the low-production and low-efficiency livestock? The rice sector is now making efforts to move the national yield average from 8.3 to 10 Mg ha^{-1} yr^{-1}, which would approach the attainable yield potential. Reaching this ambitious goal would require a further increase in fertiliser-N use by 40–50 kg N ha^{-1} for recent high-yielding rice varieties, leading to a further decline in NUE and an increase in N surplus. Hence, efforts to close the current rice yield gap must pay close attention to more precise N management with location-specific rates, splitting, timing and forms of N applied.

Kanter et al. (2016) proposed a realistic set of management improvements to the Uruguayan livestock sector to increase beef productivity by 25%. Two of the main interventions suggested are the doubling of the area of improved pastures, including more legumes in the pasture, and a modest increase in supplements fed to livestock. Both would allow an increase in the live-weight gain and a reduction in the age of slaughtering (Rivero et al., 2021). The N footprint would decrease from about 66 to 48 kg N lost per kg live weight per year, resulting in a 30% reduction of N losses from the beef sector (Kanter et al., 2016). This increase of 25% in the animal productivity would improve the NUE of the livestock component from 13.2 to 14.3%. If part of the proposed increase in improved pasture area (+0.5 Mha) were assigned to the area left by the last rice of the rotation (0.1 Mha), an increase of the country's average rice yield and a lower N fertiliser requirement would be expected (Carlos et al., 2020). In addition, the expected greater production of rice bran could offset the extra animal feed supplement suggested by (Kanter et al., 2016).

As regards improvement of soil fertility for pasture production, typical current practice is to seed the pasture over rice stubble after the floodwater is removed, taking advantage of any residual P (Gamarra, 1996), and to add 22–26 kg P ha^{-1} at the beginning of the second year of the pasture. When pasture is seeded outside the rice rotation, a similar amount of P is added at the time the pasture is sown. However, P fertilisation in natural pastures has not been shown to increase forage productivity, and causes loss of species diversity (Cardozo et al., 2017; Jaurena et al., 2021). Likewise, the main soils in the Uruguayan rice-livestock areas do not benefit from lime applications (Pinto, 2021). The proposed degree of improvement of pastures is consistent with extensive livestock production under the prevailing warm and dry climate, and a low level of investment compared with more-intensive systems.

Are improvements of the pasture-livestock sector economically viable? Assuming the average length of an improved pasture is 4 years, the average cost of establishment and maintenance are approximately US$ 45 ha^{-1} yr^{-1}. On the other hand, using the average animal productivity of this system (Simeone et al., 2008) and considering current meat values (INAC, 2020), an increase of 25% in gross animal production could result in US$ 50-60 ha^{-1} yr^{-1} of extra income, indicating that the proposal could be economically viable. In addition, an improvement in the rice component productivity is expected which would further increase profitability.

How could such changes be brought about? Both system components are strongly vertically integrated through industry, government, research, extension, and farmer associations. However, the key drivers of change must be the livestock farmers. The beef production model developed by Soares de Lima (2009) could be used to guide increasing beef productivity, including doubling the percentage of sown pastures and other management changes. Complexity has been identified as a critical issue limiting integration (Maleti et al., 2014). Asai et al. (2018) summarize various examples of integration between crops and livestock spanning organic crops and vegetables to rice in France, the USA, the Netherlands, and Japan. In all cases, developing strategies that reduce the costs associated with goods transactions and having technical support to maintain farmer networks are mentioned as a priority. In Brazil, a new integration scheme among crops, livestock and forestry for low carbon agriculture has been recently introduced, aiming to recuperate degraded pastures and mitigate soil degradation (Garrett et al., 2020). For rice, research has recently evaluated the benefits of shifting from monocropping rice to an integrated rice-livestock-soybean rotation in terms of productivity and fertilisers savings (Carlos et al., 2020). Regardless of the system, once separated, return to integration is difficult because the relevant skills and knowledge have often been lost (Martin et al., 2016). Thus, the Uruguayan rice-livestock system could become a reference for similar systems worldwide.

5. Conclusions

1. In spite of only modest mineral fertiliser N inputs, rice yields reached high levels and livestock production moderate levels, and the N balance of the whole system remained positive throughout the period analysed. This reflects the tight integration of the rice and livestock components of the system at local and national scales. Nonetheless, N losses from the system were substantial and could be reduced.
2. Changes in NUE from 2004 to 2020 followed the expected trajectory in rice and to a lesser extent in livestock, tending to decrease over time as N inputs increased. As NUE decreased, N surpluses increased in both rice and livestock, leading to greater losses, mainly through volatilisation.
3. Actions to increase system level NUE include raising livestock productivity, increased area of improved pastures and better management of the increasing applications of N fertiliser to rice.
4. The Uruguayan rice-livestock system demonstrates how crop and livestock farming can be successfully integrated to achieve multiple productivity and sustainability goals at the level of a whole country. The principles and mechanisms employed in it could also be applied in other countries and different forms of crop-livestock farming.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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